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Commercial Building Shape and Orientation: Impact on BIPV Energy Generation and HVAC Demand

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Abstract

Amid growing concerns regarding global energy use and its impact upon the environment, the existing building stock represents a significant opportunity for energy reductions, contributing about 30% of global energy emissions (Ürge-Vorsatz et al, 2012). The introduction of low energy and zero energy building targets create a metric to encourage building owners and occupiers to reduce their ongoing energy use and associated costs. Different building designs can change the energy use patterns of the building and assist in reaching low and zero energy targets but remains largely untested in Building Performance Simulation (BPS), within an Australian context. Prior research has examined the changes of weather conditions upon building energy, peak demand and thermal comfort performance using BPS models, with the overarching aim of informing appropriate low and zero-energy building strategies for commercial office buildings. This research investigates the impact of changes to building form and shape on the energy use intensity (EUI) and energy generation intensity (EGI) of commercial office buildings.

1. Introduction

The relationship between building form and energy use has previously been investigated. European studies have investigated the relationship between building volume and surface area (Straube & Eng, 2012), but found that the impact of form and orientation on energy use reduced as building size increased – smaller buildings reported changes in heating load up to 1.6 times that of with changes in the ratio of volume to surface area (Gratia & De Herde, 2003).

Studies also note that building form is typically designed to accommodate the needs of the occupants, rather than with energy as the key design goal (Straube & Eng, 2012). As a result, buildings are typically designed to be compact (low volume: surface area) and rectangular (to accommodate the narrow form requirements of both daylighting and cross-ventilation energy conservation strategies). However, improvements in passive strategies must be balanced against additional mechanical energy use resulting from less compact building forms (Catalina, Virgone, & Iordache, 2011; Choi, H., & Kim, 2012). Further, the relevance of compactness upon improved energy performance can be climate dependent, with mild and warmer temperatures showing a reduced correlation between building form and energy use (Depecker, Menezo, Virgone, & Lepers, 2001; Pacheco, Ordóñez, & Martínez, 2012).

Compactness is not the only element of building form that can impact energy performance. An examination of different building shapes confirms the importance of building compactness and suggests more complex shapes (e.g. an H-shaped building form) are more likely to increase consumption (Asadi, Amiri, & Mottahedi, 2014; Erdim & Manioglu, 2011; Raji, Tenpierik, & van den Dobbelsteen, 2017). For non-square building plans, orientation of the building can also deliver significant improvements to energy performance by maximising energy abatement from passive strategies and changing the interaction of the building envelope with the external environment (Pacheco, Ordóñez, & Martínez, 2012; Aksoy & Inalli, 2006). Research has also shown a relationship between the number of floors and heating load, while total building size has a greater contribution to cooling load, but this has predominantly been proven in cold and hot climates (Susorova, M., Rahman, Clack, & Elnimeiri, 2013; Wei, et al., 2016) – the correlation in milder climates is not as strong.

Existing research has examined the best methods to optimise building form for energy performance. Multi-criteria optimisation algorithms have been applied to building performance simulation to improve building performance, by changing the curvature of the building (Marks, 1997), and even moving building vertices to explore more complex non-prismatic forms (Yi & Malkawi, 2009). However, while this research has explored complex changes to building form, significant deviations from the cubic form create trade-offs in functionality for occupants (Fabrizio, Filippi, & Virgone, 2009).

In the context of achieving more aggressive building energy targets (low and net-zero energy targets), the relationship between building form and energy generation opportunity has not been investigated in a commercial setting. Changes in building form and their impact on residential building roof space has shown that maximising the equator facing roof space and tilt angle has the greatest impact on rooftop generation (Hachem, Athienitis, & Fazio, 2011; Topaloĝlu, 2003; Kämpf, Montavon, Bunyesc, Bolliger, & Robinson, 2010). Most research focuses upon the impact of changes to rooftop solar systems for power generation and waste heat recapture (Yip, Athienitis, & Lee, 2019), but exploration of the relationship between Building Integrated Photovoltaics (BIPV) on external facades and building form remains largely unexplored in commercial buildings. Recent forecasts of Australian office building energy use predict that these building will not reach net zero energy targets by the mid-2030s, but again only considers rooftop solar generation potential (Energy Action, 2018).

The shape and orientation of the building will have significant impacts on both energy use within the building and generation opportunities to offset this usage. This paper aims to investigate the balancing of energy use and generation potential with changes in building form and shape for commercial office buildings in the Sydney climate.

2. Methodology

Different building templates were developed covering a range of different building sizes and layouts, based on available Australian building stock data from pitt@sherry (2012) and the 2016 NABERS Annual Report. These designs were tested in OpenStudio using EnergyPlus Weather (EPW) Data for Sydney to provide representative average weather conditions, producing simulation results for annual consumption, including lighting, on-site equipment and HVAC loads (heating, cooling, fan loads, etc.). Photovoltaics have been installed on all facades and rooftops, covering 75% of the available wall and roof surface area and assumed to operate at an efficiency of 20%. The constant template building characteristics have been detailed in Table 1.

Table 1. Test building template building form (NABERS, 2016; pitt&sherry, 2012)

Location	Sydney
Lighting Power Density	6.4 W/m^2
Equipment Power Density	10.6 W/m^2
% Solar Usable Surface Area	75%
Solar Efficiency	20%
Roof R-Value	3.2
Wall R-Value	2.8
Window U-Value	3.7
HVAC System	VAV with PFP Boxes and Electric Reheat (Chiller COP 5.5)
Window to Wall Ratio	40%
Floor-to-Ceiling Height	3.6 m

Three simulation runs were conducted to establish the impact of various changes to building form on both EUI and EGI output. EUI was calculated as total annual energy use divided by total floorspace, while EGI was calculated and total annual energy generation divided by total surface area of the building.

Simulation 1: Each building floor is set at 10,000m^2 floorspace with a set floorplan length: width ratio (1:1), and the number of floors was changed between 1 and 10 floors.

Simulation 2: Total building floorspace is set at 10,000m^2 and 10 floors total, with the length: width ratio was changed to alter the layout of each floor. The length to width ratio was then changed but change the length to width ratio (0.1:1 – 10:1). NB: Length refers to the north/south facing facades, and width to the east/west facing facades.

Simulation 3: Building floors are set at a length: width ratio of 1 and a floorspace of 1,000 m^2, and the total number of floors are changed (1-32).

The average EUI and EGI results were compared to determine which building typologies were most conducive to meeting low and zero-energy targets.

3. Results

Simulation results for changes to the size and number of floors (Figure 1) show that by changing the size and number of floors, while still maintaining 10,000 m^2 of floorspace, it is possible to significantly increase the generation potential for the building. A single storied building has 4-5 times the EGI of the 10 floor building. However, these changes do not have the same impact upon EUI – while we do see a critical turning point around 2-4 floors as a minimum EUI (as the building becomes more compact and the ratio of volume to surface area increases compared to other test cases), the difference between all simulation results is only 4 kWh/m^2 per annum, and not as significant. These EUI changes are driven by the variations in each building's surface area, and the ratio between the surface in relation to its conditioned volume (assumed constant across all tests, giving a standard ceiling-floor height and a constant 10,000m^2 floorspace).

For the second simulation, results show that changes in Length to Width Ratio can have a significant impact on the generation potential of commercial office buildings (Figure 2). While total EUI of these buildings does not materially change as the length: width ratio, shifting away from a square floorplan (either increasing or decreasing length: width ratio away from 1:1) can produce a 47.7% increase in the generation potential for the building. Changes in the length: width ratio in this manner increase the surface area available for photovoltaic generation (and thus increase the EGI of the building), while having minimal material impact on the EUI of the building (as the total building size remains constant at 10,000 m^2).

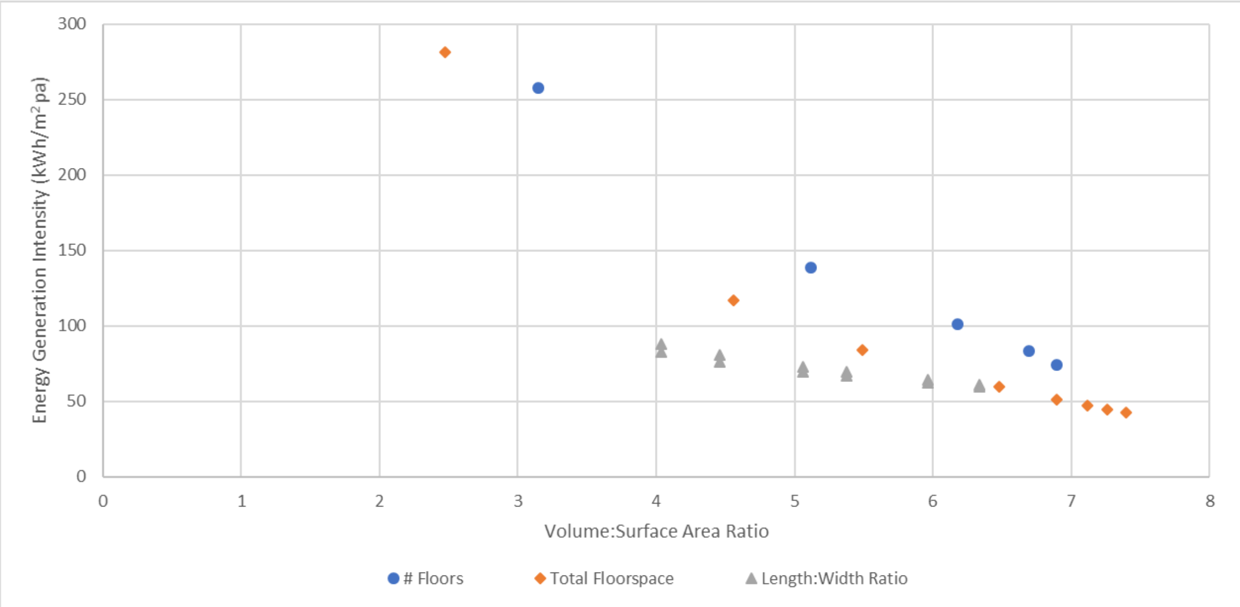

Figure 1. Energy Use Intensity/Energy Generation Intensity vs Number of Floors

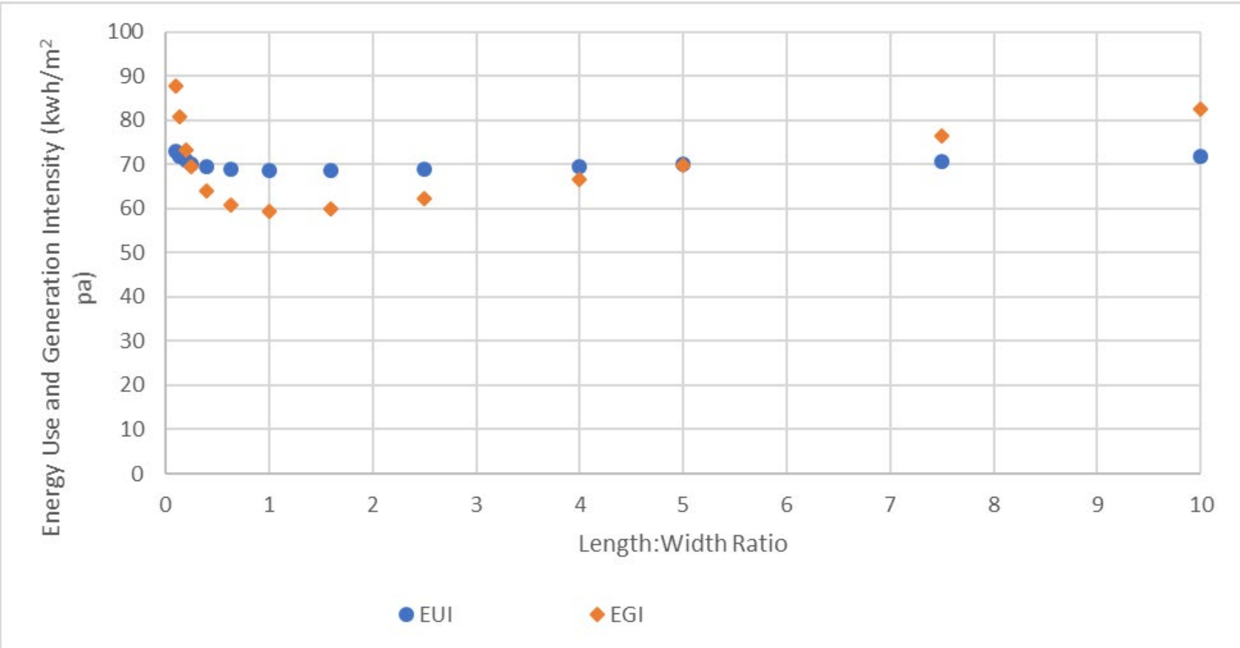

Figure 2. Energy Use Intensity/Energy Generation Intensity vs Length: Width Ratio

Finally, the third simulation run results (Figure 3) show that floor additions to the building (each time adding 1,000 m^2 floors) have minimal impact on the total building energy use intensity. However, because of the shape of each floor and the surface area of each building size compared to the conditioned volume, the generation potential is much more significant for smaller building sizes. This is predominantly driven by the more compact form of these buildings and the higher ratio of surface area (and therefore photovoltaic system capable surface area) to building volume.

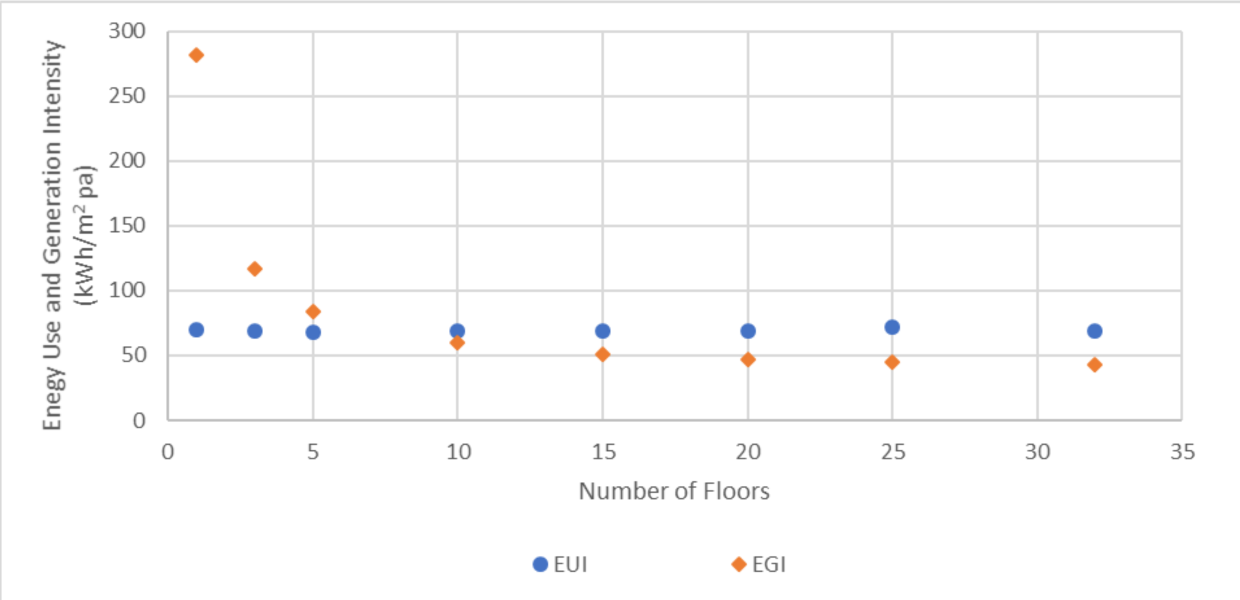

Figure 3. Energy Use Intensity/Energy Generation Intensity vs Total Floorspace

These results suggest that total energy use intensity does not vary significantly with building form but show a greater variation in the generation potential of these buildings. As lighting and equipment densities are constant across all simulations, building form will only impact EUI intensities for the HVAC components of total energy use. Figure 4 shows the comparison between the HVAC intensity for all tested buildings in the 3 simulation runs against the compactness factor for that building (treated as the ratio of the building's volume to its surface area) and highlights that the impact of building form is more keenly felt when considering HVAC energy use, with improvements of up to 36.5% resulting from changes to building form. As the building surface area increases, so too do the opportunities for heat gain/loss through these facades, hence less compact building structures While more compact building forms directly correlate with lower HVAC EUI for the results of length: width ratio variations, there are minimum turning points around a compactness factor of 5-5.5 for all other scenarios.

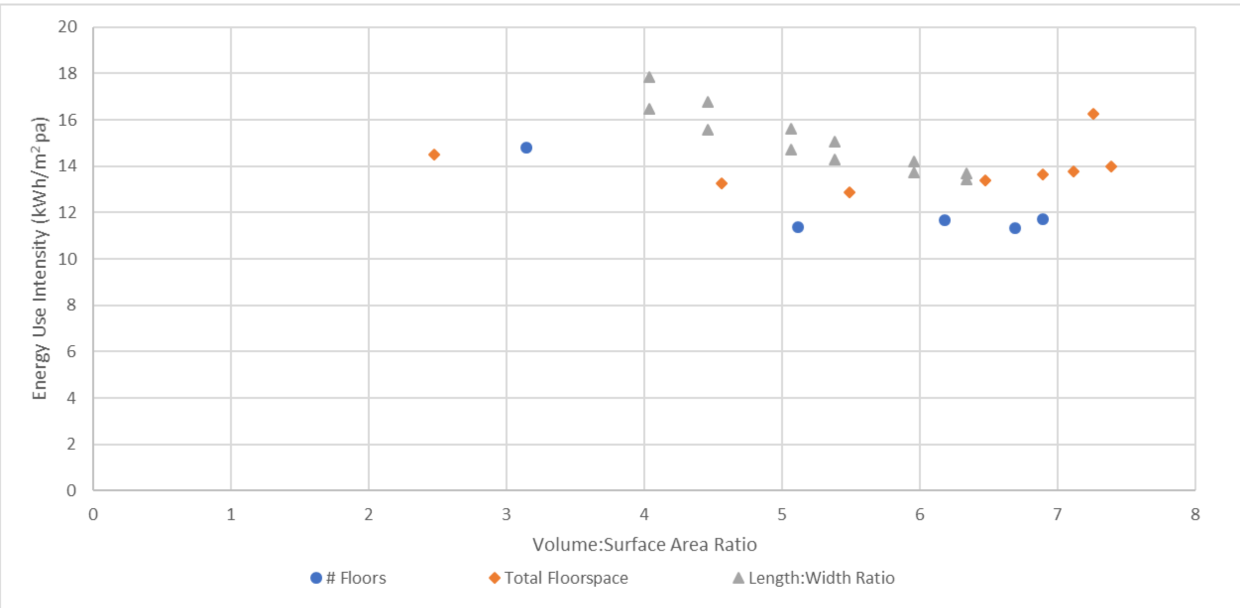

Figure 4. HVAC Energy Use Intensity vs Compactness Factor (Volume: Surface Area)

Conversely to total building EUI, these results show a greater variation in the generation potential of these buildings. Figure 5 shows a comparison between the EGI for all tested buildings in the 3 simulation runs against the compactness factor for that building. Across all simulation streams, there is a strong negative correlation between the EGI of the building simulation and compactness factor – as the building compactness factor reduces and surface area increases relative to building volume, the EGI increases, as the available façade area for photovoltaics increases and supports larger PV systems on-site.

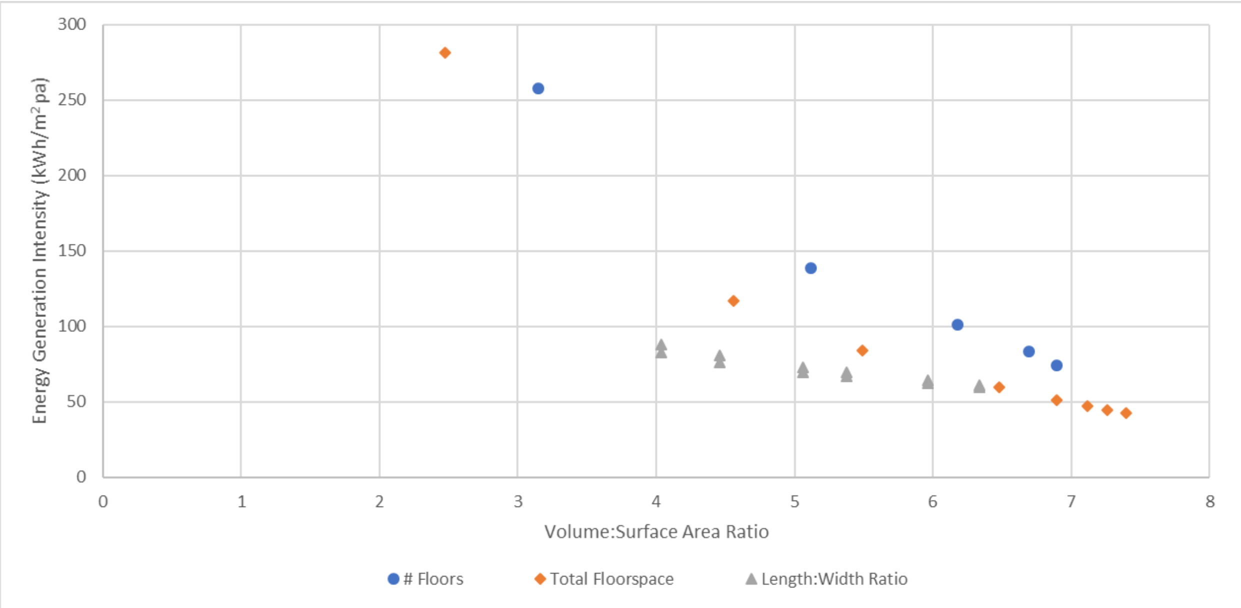

Figure 5. Generation Potential vs Compactness Factor (Volume: Surface Area)

4. Discussion

The simulation results suggest that while building form can influence building EUI, it is not a significant driver of total building EUI – across all tested scenarios, building EUI remained within a 10% variance of the maximum reported EUI. Further, as the floorspace of the building increases, there is a slight reduction in EUI across the tested building models. However, when considering the generation potential of the building, building form is much more important – a less compact building form (i.e. a building with a greater ratio of external surface area to building volume) has more surface area available for power generation through building integrated photovoltaics than a similarly sized building with a more compact form.

This is particularly relevant when considering buildings attempting to achieve low and zero energy targets; while smaller buildings will generally find it easier to meet on-site use constraints with on-site power generation, as buildings get larger, moving towards forms that increase usable façade and roof area assist in making more aggressive energy targets more achievable. However, while these buildings forms can result in significant increase in EGI, a balance must be struck between functionality and generation potential – quite often, only a marginal increase in EGI is necessary to help achieve low energy targets.

In general terms, a building's HVAC EUI falls on average as the GFA uniformly increases, as lighting and equipment EUI remain constant regardless of building size. Once a building GFA is fixed, however, HVAC EUI can be further reduced by changes the number of floors and floorplan length: width ratios, driven by the changes in surface area to building conditioned volume. While the HVAC EUI vs number of floors results show a critical point as the building height approaches the length of the floorplan (these results maintain a square floorplan), changes to the length: width ratio can provide further improvement by disrupting the dynamic of heat gain/loss with the external environment – the exact breakdown of these gains and losses are currently under further investigation.

These results show that changes to building layout and typology can have a significant impact upon the HVAC EUI, with simulated reductions of up to 36.5% from changes to the building plan, making low/zero energy targets much more achievable in the realm of commercial office buildings. While changes to building form are not applicable to existing buildings (and the difficulty in implementing more extreme changes in length: width ratios), these results do help inform new building design and ensure these new builds can limit their energy requirements, and identify the best-case scenario for minimising HVAC EUI to provide the best chance possible to achieve more aggressive building energy targets. For existing buildings, where such form changes are harder to implement, improvements can be made by making changes to the existing building envelope (for instance, improving R-values, installing glazed windows) and changes to internal HVAC operation schedules and setpoints.

Combining the results of the HVAC EUI and generation intensity of each building, there is clearly a balance to be struck to both minimise HVAC loads for a given building size, while maximising generation potential. As a building becomes more compact, the HVAC intensity decreases, before levelling out as the volume:surface area ratio passes 6:1,. Generation potential decreases as the building form becomes more compact – while decreasing the compactness factor improves the EGI of the building, maintaining a good factor to minimise EUI increase limits the potential increases in EGI to 30-50% of the generation on offer with more extreme low compactness (and therefore high external façade surface area). However, the generation potential of the buildings observed in each of the simulation runs show promising signs that introducing BIPV into facades can significantly assist in achieving low and zero-energy building targets.

There are limitations to these results, in that they treat each building as a stand-alone object, with no surrounding buildings or shading objects, and present an ideal case for on-site generation opportunities. In practice, particularly for CBD office buildings, these assumptions would not hold true, and surrounding buildings would reduce the solar exposure of the building, not only impacting internal HVAC loads, but also the output of BIPV installed in the building. Further, the simulated buildings are assumed to be in-line with average NABERS rated buildings for a Sydney climate with a single HVAC system modelled, and do not shed any light on the ability of better/worse performing buildings with Australia's existing building stock, nor on the applicability of these results to other climates. On-site generation has not been sensitivity tested against changes in photovoltaic efficiency of panels and the proportion of external façade area used for localised generation.

Future work should investigate the impact of realistic shading scenarios (e.g. single façade exposure, surrounding building shading) on annual HVAC loads and generation potential for a truer assessment of the ability of commercial office buildings to achieve net-zero energy targets. Expanding the range of building sizes and forms, as well as energy characteristics, would allow a wider assessment of the capability of the wider building stock to achieve more aggressive energy targets, and multi-year simulation against a range of weather data would provide a more comprehensive examination of the ability of these buildings to meet these targets under both more and less conducive weather conditions.

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